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EXERGOECONOMIC ANALYSIS OF A NOVEL SMALL-SCALE CHP SYSTEM FOR RURAL ELECTRIFICATION IN UGANDA

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ABSTRACT

In a world with finite natural resources and increasing energy demand by developing countries, it calls for energy researchers to come up with systematic approaches for improving the design of energy systems and reducing the impact on the environment. Exergoeconomics is a powerful tool for understanding the interconnections between thermodynamics and economics, and thus viewed as an exergy-aided cost minimization technique crucial to the design and operation of a cost-effective energy system. In this paper, the exergoeconomic analysis is applied to a small-scale CHP system integration consisting of a downdraft gasifier, producer gas combustor/heat exchanger, indirectly fired gas turbine and heat recovery steam generator. Appropriate thermodynamic expressions, and cost analysis formulas/theorems and energy investment scaling equation obtained from literature were applied. The investigated CHP system that has the potential of providing relatively higher efficiency and minimal operational difficulties, and thus attractive for rural electrification in Uganda. Exergy analysis revealed that 56.8% of the available exergy of the fuel is lost in the CHP system due to inherent irreversibilities within the system components. The study further revealed that the heat exchanger exhibits the highest exergetic loss cost of 3.555($/h) and thus consideration of modifying the heat exchanger model to reduce exergy loss is paramount.

Keywords: Combined heat and power, Energy, Exergy, Exergoeconomic analysis, Exergy destruction, exergetic cost

INTRODUCTION

A CHP system is an efficient and reliable approach to generate power and useful thermal energy from a single fuel source. The CHP system therefore makes use of the heat that would have otherwise been discarded as waste heat by recycling it back to the same system to provide the exergy needed by sub-system components instead of having an additional external fuel/power supply source. This leads to improved efficiency of the system. Exergy (availability) analysis is universally recognized in the efficiency analysis of energy systems and industrial processes since it takes into account the degree of inefficiency in each system component and thus providing the opportunities for overall system efficiency improvement.

The exergoeconomic (thermoeconomic) analysis is one of the most used exergy sub-methods that combine exergy analysis with economic analysis. The method provides a technique for evaluating the cost of inefficiency or the cost of individual process streams [1]. The primary contribution of an exergy analysis to the evaluation of an energy system comes through an exergoeconomic evaluation which considers not only the inefficiencies but also the costs associated with these inefficiencies and the investment expenditures required in reducing them [2]. The exergoeconomic analysis provides a trade-off between achieving high efficiency and the cost associated with achieving such high efficiency. Therefore the method optimizes the system efficiency with the associated cost of owning such a system.

Vast amount of research on cogeneration or CHP system analysis has been carried out using exergoeconomic analysis to establish the system performance. However it is important to note that it was not until 1980s that comprehensive work on thermoeconomics, the methodological and functional applications of it to the analysis, design and optimization of thermal systems was realized considerably [2]. The major contributions were done in 1990s, to achieve a greater standardization and formalism in the area of thermoeconomic studies. The common idea was to propose a standard and common mathematical formulation for all thermoeconomic methodologies employing thermoeconomic models that can be expressed by linear equations [3]. At that time, Tsatsaronis [4] proposed the term ‘‘exergoeconomics’’ which was defined as a part of thermoeconomics. Since the latter have been used in a general sense expressing the interaction between any thermodynamic variables and economics, he suggested that exergy based cost accounting methodologies should be indicated by exergoeconomics. Frank [5] highlights that design optimization of a thermal system means the modification of the structure and the design parameters of a system to minimize the total cost of the system products under boundary conditions associated with available materials, financial resources, protection of the environment, and government regulation, together with the safety, reliability, operability, availability, and maintainability of the system. A thermodynamic optimization, which aims only at minimizing the thermodynamic inefficiencies, may be considered as a sub-case of design optimization. Therefore exergoeconomics takes into account that exergy is the only rational basis for assigning costs to the interactions that a thermal system experiences with its surroundings and to the sources of inefficiencies within it [6].

In this paper, the researchers carried out the exergoeconomic analysis of a prospective CHP system that has the potential of providing relatively higher efficiency and minimal operational difficulties and thus attractive for rural electrification in Uganda. The target generation capacity is 100 kWe sufficient to meet electricity needs of a rural community of 250 households. Appropriate thermodynamic expressions, and cost analysis formulas/theorems and energy investment scaling equation obtained from literature were applied.

NOMENCLATURE

CHP		Combined Heat and Power
HRSG		Heat Recovery Steam Generator
HX		Heat exchanger
I	[$]	Investment
P		Component capacity
exp		Exponent
i		Inlet stream
e		Exit stream
$\dot{C}$	[$/MJ]	Cost rate
$\dot{E}$	[kW]	Exergy rate
S	[kJ/kg.k]	Entropy

Special characters

Φ	[-]	Equivalent ratio
ε	[kJ/kg]	Specific Exergy
Subscripts		
k.e		Kinetic energy
P.e		Potential Energy
ph		Pysical
ch		chemical
w		work
q		heat
o		Surrounding environment state
D		Destruciton
gen		generation
Superscripts		
x		Digression exponent

SYSTEM DESCRIPTION

The CHP system investigated in this study consists of a downdraft gasifier, producer gas combustor/heat exchanger, indirectly fired gas turbine and heat recovery steam generator (HRSG). The cycle involves steam gasification of woody biomass in a fixed bed downdraft gasifier and the producer gas obtained is then led to a combustor integrated with a heat exchanger. Compressed air and steam mixture is heated up in the high temperature heat exchanger to turbine inlet temperature. The exhaust gases from the turbine are led to a heat recovery steam generator. The generated steam is used for both injection into the gas turbine and as a gasifying agent. Flue gases from the combustor are used for preheating the combustion air. The system configuration is shown in Fig. 1. The design parametric values obtained under previous studies of this CHP system are shown in Table 1.

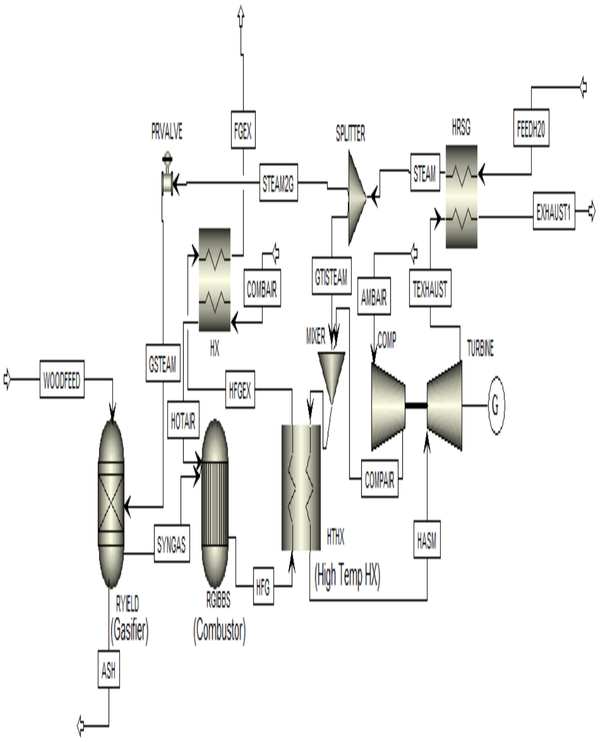

Figure 1 Schematic of the CHP system

Table 1
Design parametric values for the CHP system

Description	Value	Reference
Gasifier-Allothermal gasification with steam as gasifying medium		[7]
Gasification temperature	820°C	
Wood feed rate with 20% moisture	0.02 kg/s	
Steam Flow rate at 500°C, 1 bar	0.012 kg/s	
Net producergas flow to the combustor at 700°C	0.02 kg/s	
Producergas Combustor		[8]
Equivalent ratio, Φ	0.25	
Adiabatic flame temperature	1353°C	
Flow rate of combustion products to heat exchanger	0.308 kg/s	
Combustion air inlet temperature	250°C	
Heat Exchanger		[8]
Hot stream outlet temperature (Fluegas to air preheater)	346.8°C	
Cold stream inlet temperature	250°C	
Cold stream exit temperature to micro gas turbine	950°C	
Cold stream flow rate (turbine working medium)	0.516 kg/s	
Heat exchanger effectiveness	0.635	
Micro gas turbine		[8][9][10]
Turbine exhaust temperature to HRSG	587°C	
Isentropic efficiency; Compressor, Turbine	80%, 82.5%	
Heat recovery steam generator		[10]
Cold water inlet temperature	25°C	
Steam parameters exiting the HRSG; Temperature, Pressure	500°C, 4.5 bar	
Temperature of exhaust from the HRSG	300°C	

METHODOLOGY

The thermo-economic optimization approach for conceptual biomass gasification process design is explained as follows. An equilibrium model can be derived from experimental data to account for the formation of gasification products under changing operating conditions. This model can then be integrated to a process simulation superstructure for which the selection of processing parameters and operating conditions are determined based on the desired producer gas properties into the combustor/heat exchanger and its effect on the whole energy conversion system. Process equipment cost and sizing parameter functions are related to gasification operating conditions.

The cost estimates of the CHP configuration was carried out using known cost analysis formulas and theorems available in published literature, equipment manufacturers, and applying the energy investment scaling equations available.

A thermoeconomic evaluation was done to compare the exergy requirements and costs involved by striking a balance between the two. Thermoeconomic concepts were then applied to the system configuration. The power system was evaluated on the basis of the first and second laws of thermodynamics. A thermoeconomic analysis using the theory of exergetic cost was performed in order to determine the production costs of electricity and steam/heat. The main components of the system that present significant opportunities for exergy recovery or those that present high risk of exergy destruction shall be dealt with in the analysis. These key components include the gasifier, combustor, heat exchanger, micro gas turbine and the heat recovery steam generator. Other components with low value heat and small components in the system configuration are assumed to have limited impact on the system performance and thus their exergy analysis is left out. Scaling of component cost data to account for different capacities was estimated using the formula:

$$I_c = I_{c,b}(P/P_b)^x \tag{1}$$

where I_c is the component investment at capacity P, $I_{c,b}$ the component cost at capacity P_b and x is the digression exponent(exp), taken to be 0.7 in power plants investment.

EXERGY AND EXERGOECONOMIC ANALYSES

The exergy analysis is a method that combines both the First and Second law of thermodynamics for the design and analysis of thermal systems The objective in exergy analysis is to identify areas in the system where exergy destruction and losses occur and their magnitude so that attention can be put on the components of the system that offer the greatest opportunities for improvement. The change in exergy of a system in most processes involves exergy destruction brought about by presence of irreversibilities and thus the exergy transferred across a given system is less by irreversibility losses. In general, the specific exergy denoted by 'ε' is evaluated using the expression

$$\varepsilon = \varepsilon_{ke} + \varepsilon_{pe} + \varepsilon_{ph} + \varepsilon_{cl} \tag{2}$$

Where $\varepsilon_{k.e}$ and $\varepsilon_{p.e}$ are specific exergy due to kinetic energy and potential energy respectively. ε_{ph} is physical exergy (exergy due to temperature and pressure difference), ε_{ch} is chemical exergy (exergy due to chemical reaction such as combustion of fuel in the combustor but can also occur without a chemical reaction).

In the present analysis, the CHP system is assumed to be at steady state conditions with negligible effects of kinetic and potential energy, the combustion gas is assumed to have ideal properties and the streams utilize the ideal gas model. The atmospheric conditions are taken to be 25°C and 101.325 kPa.

Exergoeconomic analysis is a technique that combines exergy analysis and economic principles that guide the design and operation of a cost-effective system which would otherwise be difficult to achieve using conventional energy analysis and economic evaluations where each is analyzed separately. Therefore exergoeconomics is an exergy-aided cost minimization technique that provides a rational basis for assigning costs to the interactions that a thermal system experiences with its surroundings and to the sources of inefficiencies within it. In exergy costing, a cost is associated with each exergy stream. Therefore the cost rate $\dot{C}$ for entering and exiting streams of matter with associated rates of exergy transfer $\dot{E}_i$ and $\dot{E}_e$, Power $\dot{W}$, and the exergy transfer rate associated with heat transfer $\dot{E}_q$ can be written respectively as[6].

$$\dot{C}_i = c_i \dot{E}_i = c_i(\dot{m}_i e_i) \tag{3a}$$

$$\dot{C}_e = c_e \dot{E}_e = c_e(\dot{m}_e e_e) \tag{3b}$$

$$\dot{C}_w = c_w \dot{W} \tag{3c}$$

$$\dot{C}_q = c_q \dot{E}_q \tag{3d}$$

Here c_i, c_e, c_w and c_q denote average costs per unit of exergy in dollars per megajoule ($/MJ)

A cost balance applied to the k^th system component indicates that the sum of cost rates associated with all exiting exergy streams equals the sum of cost rates of all entering exergy streams plus the appropriate charges due to capital investment and operation and maintenance both summed up as $\dot{Z}_k$ in the expression below.

$$\sum_e \dot{C}_{e,k} + \dot{C}_{w,k} = \dot{C}_{q,k} + \sum_i \dot{C}_{i,k} + \dot{Z}_k \tag{4}$$

Evaluation of physical and chemical Exergy

The physical exergy of a closed system at a specified state is given by the expression

$$E_{ph} = (U - U_o) + P_o(V - V_o) - T_o(S - S_o) \qquad (5)$$

Where U, V and S denote, respectively the internal energy, volume, and entropy of the system at the specified state and U_o,V_o and S_o are the values of the same properties when the system is at restricted dead state. The specific physical exergy associated with a stream of matter is given by

$$\varepsilon_{ph} = (h - h_o) - T_o(s - s_o) \qquad (6)$$

The exergy destruction E_D due to irreversibilities in the system is given by Gouy-Stodola theorem expressed as

$$E_D = T_o S_{gen} \qquad (7)$$

The standard specific chemical exergy of fuels is close to its higher heating value [6]. The standard chemical exergy of gases and gas mixture is obtained from tables of standard molar chemical exergy.

RESULTS AND DISCUSSION

Table 2

Stream exergy for the CHP system

Stream flow	$Exergy\ Rates\ (kW)$		
	$\dot{E}_{ph}$ +	$\dot{E}_{ch}$ =	$\dot{E}$
Wood feedstock	0.0	360.0	360.0
Steam to gasifier	10.3	5.8	16.1
Producergas exiting the gasifier	287	48.2	335.2
Combustion air to combustor	39.6	0.0	39.6
Combustion products exiting combustor	357	0.0	357
Combustion products existing HX	45	0.0	45
Turbine working medium entering HX	35.5	0.1	35.6
Turbine working medium exiting HX	312.3	0.1	312.4
Air to compressor	0.0	0.0	0.0
Turbine Exhaust to HRSG	152.4	0.1	152.5
Exhaust stream exiting the HRSG	5.0	1.3	6.3
Steam exiting the HRSG	33.5	21.6	55.1
Feed water to HRSG	0.0	0.0	0.0

Table 3

Exergy Destruction in the CHP components

Component	$Exergy\ Destructio$		
	$Rate\ (kW)$	$\%^{1}$	$\%^{2}$
Gasifier	29.1	14.2	8.1
Combustor	17.8	8.7	4.9
Heat exchanger	35.2	17.2	9.8
Microturbine	31.4	15.4	8.7
Heat recovery steam generator	91.1	44.5	25.3
Overall CHP system	204.6	100	56.8

[1] Exergy destruction rate within a component as a percentage of the total exergy destruction rate.

[2] Exergy destruction rate within a component as a percentage of the exergy rate entering the CHP system with the fuel.

Table 4
Exergetic cost rates of the exergy loss

Component	Cost rate ($/kJ)	Actual cost of lost exergy ($/h)
Gasifier	0.084	2.444
Combustor	0.053	0.943
Heat exchanger	0.101	3.555
Microturbine	0.068	2.135
Heat recovery steam generator	0.035	3.189

From the exergy analysis results shown in Table 2 and Table 3, the overall exergy destruction is obtained as 56.8%. The CHP plant therefore suffers from irreversibilities associated with chemical reaction, heat transfer and friction. The combustor (and gasifier) experiences all the three forms of irreversibility whereas the HRSG experiences heat transfer and friction. Exergy destruction in the adiabatic micro gas turbine is caused mainly friction. There exists opportunities for enhancing the heat recovery from the Heat recovery steam generator if additional use of the steam generated is explored. The inefficiency of combustion can be reduced by preheating the combustion air and reducing the air-fuel ratio. Exergy destruction associated with heat transfer decreases as the temperature difference between the streams is reduced. The exergy destruction within the turbine and air compressor decreases as friction is reduced. In conclusion, an endeavor made in improving the performance of one or more components in the CHP system has potential for improving the overall system taking into account the cost implications.

From the exergetic cost analysis shown in Table 4, the heat exchanger presents the highest cost associated with exergy loss. Modifying the design of the heat exchanger to minimize the exergy loss would therefore provide an economic opportunity in the improved CHP system. Generally, additional investment aimed at reducing exergy loss in any of the analyzed components of the CHP system will provide an economic advantage relatively.

CONCLUSION

An exergoeconomic analysis was performed on the small scale CHP plant capable of delivering 100kWe power. Correlated cost data has been used to estimate the actual cost of the CHP components. Exergy analysis revealed that 56.8% of the available exergy of the fuel is lost in the CHP system due to inherent irreversibilities within the system components. The study further revealed that the heat exchanger exhibits the highest exergetic loss cost of 3.555($/h) and thus consideration of modifying the heat exchanger model to reduce exergy loss is paramount. Hence the exergy analysis locates the system or component where necessary attention should be put to improve the performance of the designed plant.

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